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The RF PRISM concept for pushing forward the antenna size barrier in space based Radar

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Abstract: RF PRISM is a new space antenna concept where an array is fed through a mesh of points on the antenna back face with RF signals transmitted (or received) by another satellite called illuminator and usually offset by 100 Km on the same orbit. Basically the PRISM deviates, amplifies, and beam forms the signals passing through it and travelling between the illuminator and the earth. Providing that the speed vector and the main earth viewing axis have equal incidence on antenna plane the antenna deformation control or knowledge requirement is relaxed by a factor 10. Moreover there are no longer cables between the antenna panels. RF PRISM therefore enables deployment of very large antenna in space. The illuminator satellite is not constrained by the illumination function (a few Watts and a 1m2 antenna), but just by the central payload function moved away from the satellite bearing the antenna. This can be a micro-satellite.

Among others applications, this concept opens up new prospects for space-borne SAR requiring a very large antenna structure either for very low frequency (P-band), or for very high altitude (high revisit), or for single pass interferometry (two antennas). Optionally it can be combined with the SAIL that is an another concept circumventing large antenna constraints (vertical antenna with gravity stabilisation).

A short overview of the concept applied to Radar has already been presented at IGARSS 2000 (Honolulu) and published in proceeding (/2/). This papers goes more in details in term of practical implementation of the concept.

1 RF PRISM CONCEPT

1.1 Generic geometry

This concerns an active array antenna whose the signal supplying (supplied by) the radiators comes (goes) through the back of the antenna from (to) a more or less remote RF source (receiver). This type of approach as known to date is that of the RF lens and we know that this device leads to strong tolerance to deformations, provided that the antenna beam remains in a direction close to that of the illumination and that the source is sufficiently remote in relation to the antenna's dimensions. As a result, application to a large space antenna has a limited interest, as the source must be set on an extremely long mast.

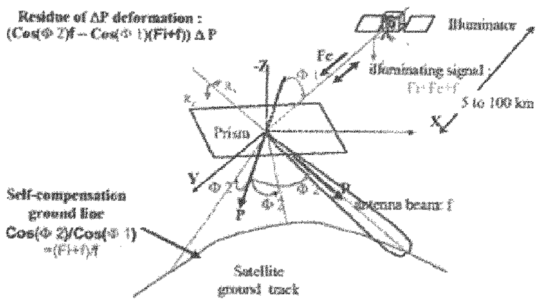

Figure 1:Generic geometry

In our study, the source is rejected far away on another satellite located on the same orbit (in front or behind). The antenna does not work like a lens but like a prism as it achieves considerable deviation of the wave from a horizontal illumination axis to a vertical or oblique earth sighting axis. The deformation immunity is achieved when these two axis have an incidence (angle to the antenna plan vector) on the antenna plan that meet conditions detailed here after function of the frequencies used on illumination (back) side and on mission (earth) side, a particular case being the identity of the incidences.

Figure 1 shows the generic geometry. Illuminator I is located on axis –Y, the speed vector is on Y in any direction. The vector P is normal to the antenna plane. The antenna beam aims to ground a range set by the mission (vector R).

1.2 Internal and/or external frequency translation

Since the prism performs an amplification, a frequency translation in the prism is used on both transmit and receive links to earth.

The illuminating frequency is F+f, f is the frequency used by the mission on the earth side, F is positive or negative. In the generic case the frequency translation is the combination of two translations, one said internal using a translation tone of frequency Fi generated in the prism and an another said external using a tone of frequency Fe received from (or whose reference used for building it by multiplying is received from) the illuminator, and in that F= Fi +Fe. In presence of several illuminators (can occur for satcom application where a cluster of illuminators gives an equivalent

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cluster of beams) only one called focus transmits the tone Fe.

1.3 Self-compensating geometry with respect to Antenna Deformations

Here we analyse the prism working on transmit path only. When Fe = 0, every thing applies to the receive path too as the means are reciprocal. The implementation of the external translation in receive mode is detailed in /1/. The preferred solution to get the same behaviour in receive as in transmit as is to use Fe with a negative translation (which move away from the desired frequency on the side of the prism) and to compensate that by an internal translation (or an increase of the internal translation) of value 2 $|Fe|$.

We can model the antenna by a field of deformations about a mean plane (unflatness type) Δp along P. The coplanar deformations (normal to P) are by nature much less significant.

Self-compensation is obtained when, for any point of the antenna, the point projected on the wave plane normal to R sees the wave with an unchanged phase. That is when the projection of Δp on R has a phase value opposite to that of the projection of Δp on IA. For an illuminator sole or combined with the focus, the phase values of the two projections are respectively - $2\pi \Delta P \operatorname{Cos}(\phi 2) f/C$ and $2\pi \Delta P \operatorname{Cos}(\phi 1)(F+f) /C - 2\pi \Delta P \operatorname{Cos}(\phi 1)Fe /C$, with $\phi 2$ and $\phi 1$ being respectively the incidences on the prism of R and AY. Self-compensation is obtained when: $\operatorname{Cos}(\phi 2)/\operatorname{Cos}(\phi 1) = (Fi+f)/f$.

The external translation does not play any role in the self-compensation geometry. The Earth sighting axis that meet the self-compensation condition are on a cone whose axis is normal to the prism.

The phase seen by the projection in the wave plane of any antenna point will not vary with deformation but the position of the projection in this wave plane will move. There are two cumulative shifts within the wave front plane, one related to the illumination path in $\Delta P \operatorname{Sin}(\phi 1)$ and the other one related to the mission path in $\Delta P \operatorname{Sin}(\phi 2)$. The validity of the concept may be affected in presence of a significant gradient for the phase and amplitude distribution within the wave plane. If this distribution is brought by the prism, only the downstream shift (at illumination side on receive path, at mission side on transmit path) counts. We will see later an option of the concept allowing for correcting theses shifts effects.

1.4 Self-compensation residue and mission field of view.

For a change $(\delta\phi 1,\delta\phi 2)$ of the geometry, the self-compensating residue is as ΔP $(-\operatorname{Sin}(\phi 1)\ (Fi+f)\ \delta\phi 1 + \operatorname{Sin}(\phi 2)\ \delta\phi 2\ f)$. Only the second component is of interest here as it is that which results from the mission field of view requirement.

We consider a maximum residue of 0.1 ΔP, that is to say a reduction by 10 of the flatness requirement (from $\lambda/20$ to $\lambda/2$ for instance). For Fi=0, a solution can be $\phi 1 = \phi 2 = 45°$ et $\delta\phi 2 = +/- 10°$. For Fi positive, we can improve the mission field of view or the deformation relaxation. With (Fi+f)/f. = 5, we have $\phi 1 = 79°$, $\phi 2 = 11°$ and there is not any more real limit on mission field of view for a 0.1 flatness relaxation factor. However, positive Fi made the position of self-compensation sighting more sensitive to prism attitude error.

The flatness requirement is typically relaxed from $\lambda/20$ to $\lambda/2$.

1.5 Electronic correction of deformations and attitude

If the deformation can be known or measured, the deformation residue $\Delta P(\operatorname{Cos}(\phi 1)(Fi+f) - \operatorname{Cos}(\phi 2)f)$ can be removed at the level of the antenna phase shifters. In this case the relaxation factor $(\operatorname{Cos}(\phi 1)(Fi+f) - \operatorname{Cos}(\phi 2)f)$ applies to the accuracy δP of deformation knowledge and there is not anymore requirement on flatness itself. Considering that a knowledge of $\lambda/2$ can be easily achieved, the electronic correction removes both flatness and mission field of view constraints. As an option, the measurement all along the antenna of the phase of the illumination signals provides an elegant way to determine the deformation. That enables also measurement and correction of the attitude pitch and yaw errors.

The electronic correction can also apply for the shift effects within the wave plane (see § 1.3) of the phase and amplitude distribution using the knowledge of the two components of the shift: $\Delta P \operatorname{Sin}(\phi 1)$et $\Delta P \operatorname{Sin}(\phi 2)$. For that later correction, the concept provides no relaxation with respect to the case of a standard antenna. However, the shift effect correction is less exigent than the basic flatness effect correction, taking into account the low gradient of most of the distributions laws.

1.6 Geometry examples with Fi = 0

- Geostationary communication: We generally aim around the nadir. P vector is within the orbit plan and inclined by 45° with respect to the vertical. The deviation is simple. The relaxation factor is 10 (field of view < +/- 10°). On both illumination and mission side the antenna area is used with an efficiency of 0.7.
- Low orbit, side looking, communication or radar: This is obtained from the previous geometry by a

roll tilt by 45° (roll field of view from 35° to 55°) since the prism working is independent of the roll position.

- SAIL (/3/,/4/) type satellite for radar or telecom on low orbit: The SAIL geometry is characterised by a vertical antenna plane (P is horizontal, orthogonal to AZ), one of its interests is the enable gravity gradient stabilisation of the antenna and therefore to ease large antenna flying. For a lateral main sighting axis inclined toward earth by 45°, as in the previous case, the self-compensation condition is obtained when P vector is deviated from the orbit plan by 55°. The wave deviation realised by the prism is combined. The efficiency for use of the surface is 0.57 both on illumination and mission side.
- Low orbit mission (radar or telecom) based on a swath mode. Similar geometry as geostationnary telecom but with a field of view achieving a defiling swath. With P in the orbit plane, the cone of self-compensation sighting encounters the earth according to a line globally transverse to the satellite track. The deformation relaxation is total if the field of view is a swath that follows this line.

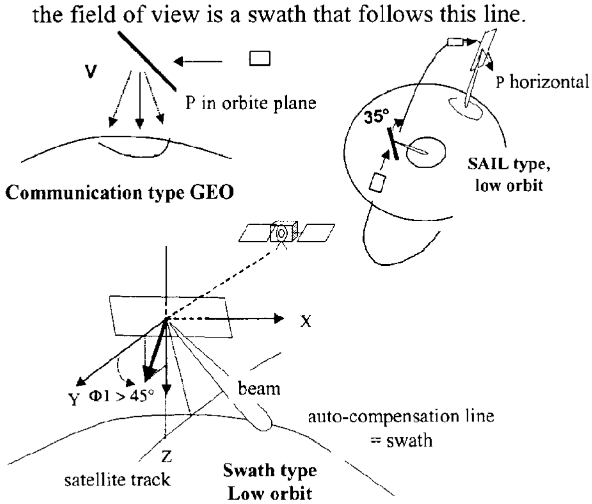

Figure 2: Geometry examples with Fi=0

1.7 Sampling of the coupling between prism faces

The antenna is divided into tiles containing a single coupling point between faces. This coupling point realises the frequency translation and the deviation of the wave. The later is based on a phase shifting and needs a delay line too (except in case of limited relative bandwidth). The local deformation within the tile is not compensated but the flatness control is above all a constraint at the scale of the whole antenna mainly because of the partition into deployable panels. Nevertheless, because of the overall deformation, perfectly flat tiles may deviate from the antenna main plane and several tiles may be required per antenna panel, that depends on the deformation profile. With a deformation whose scale is the antenna dimension (wash-bowl profile, general case of thermal deformations) and the amplitude limited to $\lambda/2$, a single tile per panel is sufficient provided that there are at least 10 tiles in each dimension. (see figure 3)

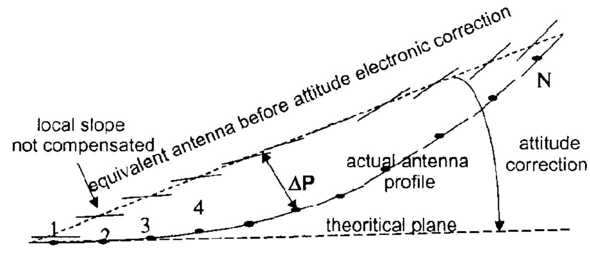

Figure 3: Local scale errors not compensated

If we know the deformation, the tile miss-alignments with respect to the main antenna plane can be corrected at the level of the phase shifters of the array antenna and the tile sampling can be relaxed or the deformation scale reduced. However, for theses local corrections within the tiles, we do not benefit from the relaxation in term of knowledge accuracy as we do for the correction between tiles (cf §1.5). That is of little relevance since the knowledge is always much better locally as soon as a deformation model, even simple, is used (whether or not the knowledge relies also on measurements).

A cluster of illuminators gives a cluster of beams. With several illuminators the aperture of the cluster of beams also drives the sampling in order to limit the grating lobes. A 7 λ x 7 λ effective (as seen once projected in the wave plane) sampling enables a 2° cluster aperture (/1/).

2 PRISM OPERATION IN PRESENCE OF ERRORS (ATTITUDE, ILLUMINATOR POSITION, , FREQUENCY) OR MULTIPLE ILLUMINATORS

2.1 Prism modelling as a modified lens

Let us refer to the projection of the prism on planes orthogonal to AY and R respectively as the equivalent rear and front faces of the prism. Generally, these transforms from the real faces to the equivalent ones do conserve neither length nor angle. In a simple deviation prism case, a line of the real face orthogonal to the plane (AY,P,R) is kept orthogonal to this plane with no length change. The other line of the real face orthogonal to the first one has got its transforms orthogonal to those of the first line but there is a ratio $\mathrm{Cos}(\phi 1)/\mathrm{Cos}(\phi 2)$ between the front and the rear transforms.

The prism's basic role can be decomposed as follows, no matter the order of the operations:

- Translation Fi with the same phase for all the points of one of the two equivalent faces. In reality, that translation is applied on the real face with addition of a delay or phase profile on the antenna as an inclined plane
- Translation Fe at the level of the equivalent or of the real rear face with the phase according which the translation signal is received on that real or equivalent rear face.
- Linking each point of an equivalent face to the corresponding one of the other equivalent face with a delay identical for all the point couples. In reality, the delay is applied on the real face according to a profile as an inclined plane.

2.2 Illuminator Deviation and Multi-illuminator Operation

It can be shown (/1/) that the prism works as a lens whose the illuminator would be located in a deviation frame RxRz (see figure 1) derived from the actual deviation frame XIZ by the same transformation as those which applies between the equivalent rear and front faces, followed by an amplification/reduction as (Fi+f)/f for what is related to the deviation of the focus with respect AY axis and as (Fi+Fe+f)/f for what is related to the deviation of the illuminator with respect to the focus.

2.3 Behaviour with Respect to Prism Attitude

A change in attitude of the prism combines two effects as far as the position on the beam footprint is concerned, with the effect induced by the movement of the illuminator in a reference system related to the prism and the direct effect (the only one for a conventional antenna) of the movement of the reference system. From what is said earlier, the induced effect related to any illuminator if Fe =0 or to the focus is scaled by the actual motion of that illuminator in the prism frame, that is to say by the direct effect, and by the ratio (Fi+f/)f. For great value of (Fi+f/)f, the attitude sensitivity is therefore increased.

The roll effect of a prism remains unchanged as compared with a standard antenna. Only the direct effect applies since the illumination is invariant with roll. If the prism is in self-compensation geometry, an attitude error around an axis contained in the prism and orthogonal to roll axis has no effect since it can be considered as a deformation transverse to the prism plane. The induced effect scaled by (Fi+f/)f impacts only for attitude error component orthogonal to the two previous, that is to say on yaw for a satcom type prism, or on pitch for Sail type prism.

2.4 Effect of frequency unstabilities and of the Δf/f

In absence of Fi, the deviation between different illuminators or between an illuminator and the focus is affected by the f variation on account of the transfer function of the deviations as (F+f)/f. For Δf/f of few % and a total cluster beam aperture of 2°, the impact is kept limited. In the case of a single illuminator located near the focus (if any), there is no sensitivity to Δf/f.

Fi unstability adds an offset of the whole beam cluster, however it depends on Fi value and can be avoided by using a delay ramp rather than a phase ramp for the application of Fi on the real face (see § 2.1).

See /1/ for more details.

3 ANTENNA ARCHITECTURE

The prism antenna is a signal deviator. Mission related beam scanning is added on around a fixed base deviation. Deviation of the base must be obtained in principle by a delay (except in the case with a low relative band where phase shift is adequate for the entire deviation introduced at each point between the rear side and the front side. The delay function aims, by completing the geometrical delay already existing between two corresponding points of the front and rear equivalent sides, at make the total delay constant for all the couples of points. The delay function is the opposite of the geometrical delay, it is two-dimensional for a combined deviation. As the delay values are of the order of the antenna dimensions, we need to sample this function broadly to reduce the number of delays so as to be able to introduce them in the inside of the antenna. The antenna is divided into tiles containing a single coupling point. The deformations are not compensated for inside the tiles. However, this does not detract from the advantage of the concept, as stiffness is above all difficult to maintain on large dimensions (see §1.7)

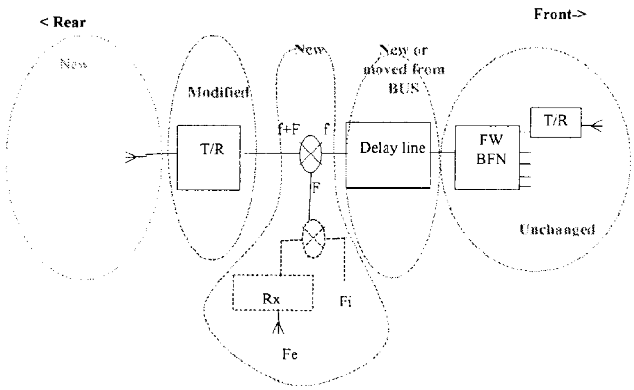

Figure 4: Tile RF Architecture

Figure 4 shows the architecture inside a tile. The tile can be seen as a tile of standard active antenna with added components.

The part forward of the delay remains unchanged as compared with a current array antenna (which also needs fixed and tunable delays but that we can leave in the platform). The beam forming network (BFN) is not made of equal length branches since it must reproduce the portion of the delay function seen in the tile. It can be shown (/1/) that the rear radiator can be very small (1,4 λ_{F+f} per 1,4 λ_{F+f}) and that the whole rear antenna is very lacunary. The rear BFN can be avoided or considered as an integral part of the rear radiating element. It is possible to keep the rear side available for possible heat protections or stiffeners as is usually the case. The Rear amplification / reception involves very low power levels (0.5 W, /1/) and can thus be seen as a modification of primary amplification/reception as found in standard active array antennas to relay signals from or to the platform.

We can conclude that:

- Putting aside the frequency translation, the only significant difference as compared with a conventional architecture is the introduction of a fixed delay inside the tile. The variable delay for which the need and the sizing remains unchanged (depending on the bandwidth and the mission off-steering around the base deviation) must also be in the tile here.
- In the case where the tile is the panel to be deployed, the fixed delay introduces no additional constraint, indeed rather the opposite in that it replaces the RF transmission/reception cable connecting the panel to the platform which makes for greater overall length and complicates deployment.

The principle must be applied with discernment in order to gain the maximum advantage. For example, in the case of an antenna with an elongated shape, we shall seek to compensate for deformations on the length only, all the more as the latter corresponds to the axis of deployment resulting in the main mode of deformation.

4 APPLICATION TO SAR

4.1 SAR prism geometry

The P vector of a space-borne SAR antenna is usually orthogonal to the speed vector V and tilted toward earth. As shown by Figure 5, a SAR prism is achieved by a second antenna tilt either on pitch or on yaw to enable the illumination, the SAR sighting range (vector R) being kept unchanged and orthogonal to V.

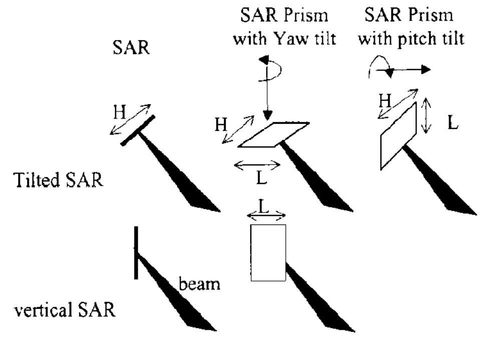

Figure 5: SAR prism as seen from the illuminator

In the case of the Vertical/ Sail Prism (see 1.6) the illumination with a yaw tilt keeps intact the other vertical or SAIL advantages. With Fi=0, the yaw tilt is limited (35°) and it is still possible to have solar cells on the back of the antenna on a dawn dusk orbit and to keep there another advantage of the SAIL concept (no need of solar array)

External translation is not necessary (Fe=0) in Radar since a single illuminator is generally used. A great Fi value reduces the illumination tilt and improves the deformation immunity or the field of view (see §1.4).

4.2 Fully self-compensated system

The Prism concept allows compensation or correction of all the deformations and attitude errors except the roll axis attitude. However the later is the one that is the easiest to measure and to correct by the radar itself using the fact that the image radiometry is attached to the attitude and that the image geometry is not.

4.3 Radar Timing constraints

For radar, echo reception must occur outside transmissions. If the same illuminating frequency is used on transmit and receive, this timing condition must be verified both for the antenna and the illuminator. If that case the distance between the two satellites must be locked on a multiple of the ambiguity. A control error +/- δd of that distance affects by +/- $2\delta d/C$ the position of the echo in the timing diagram of illuminator. Transmit and receive are still separated at the illuminator level if the timing control considers that the echo at the level of the prism is virtually enlarged on each side by the value $2\delta d/C$ or that the swath is virtually enlarged of

$2\ \delta d/\ \mathrm{Sin}\ (i)$. This virtual swath enlargement applies only for the timing (not at all for ambiguity or any other swath related constraint) and affects the required range of relative tuning of the PRF on a one per one base (at least). Therefore, considering as worse case a mission with a 10 km swath at 30° incidence, a

doubling of the relative PRF tuning range enables a tolerance in inter-distance of +/- 10 Sin(i)/ 2 = +/- 2.5 km. For a mission of much larger swath this constraint is relaxed accordingly.

The constraints related to second Fi frequency have to be traded against those of the distance control.

5 P BAND SAR (λ= 75 CM)

5.1 Deployment of a very large antenna

The large antenna area is the main design constraint of a P band SAR satellite. At least 50 m^2 should be provided to enable significant incidence domain and revisit performance.

The Prism approach roughly removes all the flatness constraint. Indeed, the deformation constraint can be relaxed up to +/- 37 cm (λ/2). The constraint can even be totally freed since the poor deformation knowledge accuracy (+/-37 cm) required for the electronic correction can be obtained intrinsically or via rudimentary devices (angular coders at hinges for example). The +/- 37 cm control or knowledge envelop does not include the attitude error whose electronic correction (see § 1.5) needs phase measurement on only three or four distant points of the antenna.

Without flatness constraint the large antenna can be obtained with inflated structure or by rigid panels deployed with rudimentary mechanisms (eg: shape memory). Two other Prism advantages particularly ease the deployment of a large antenna: 1) There is not any more RF cable to circulate along the antenna. 2) The antenna can be made of several leaves not fully attached each other, which eases two-dimensional deployment as shown by figure 6.

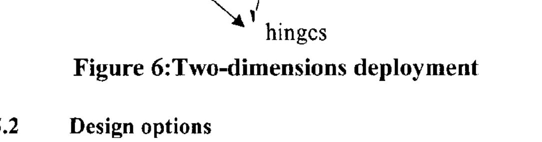

Figure 6:Two-dimensions deployment

5.2 Design options

Antenna folding and deployment are not the only satellite design constraints. The antenna has to be powered and attitude controlled. A SAIL type prism is advantageous from theses view points but it may induce a significant extra antenna area if highest incidence is smaller than 55° and it does not fit well long antenna and consequently large swath (>50 Km). A tilted prism may optimise the antenna area but the attitude control (and stability) becomes a major concern. Indeed, such a large body in space is exposed to a significant gravity gradient torque and has low structural stiffness. The torque is the key sizing factor of the attitude control system in the tilted case whereas it does naturally most of the control job in the Sail case. The stiffness has to be kept compatible with the control system, which is much more difficult in tilted case as that control system is much more active. In tilted case, the limitation of the gravity torque leads to a long antenna (for a given antenna area) and to an illumination with yaw tilt.

6 SINGLE PASS INTERFEROMETRY (X BAND)

A straightforward way to exploit prism for single pass interferometry is to have the base and the two antennas within a common plane. Doing so, the single pass interferometry is mainly a matter of deployment and orbiting of a large planar structure, as for P band. There are however major differences. The frequency is at the other edge of the spectrum (X or Ku) because of the need to limit the base length. Consequently electronic correction should be implemented in order to relax the deformation control beyond the basic λ/2 (1.5 cm in X band) allowance offered by the self-compensation. The two antennas must use a distinct Fi translation in order to separate the two receive channels. The two antennas should be identical in order to enable the ping-pong mode (alternate pulse transmit on each antenna) which doubles the effective double length size.

The antenna is rather short with respect to the base, which enables the Sail Prism option. In Sail case the roll is cyclic at twice the orbit period, few interferometry images per orbit taken on flat areas (sea) enable a retrieval of the roll error.

However, the knowledge attitude accuracy may be insufficient for absolute DEM, moreover the system does not control or compensate the baseline length. The system can be focused on accurate relative DEM as, on account of the reduction of size constraints, the two X antenna can be large and the phase noise very small (good SNR and ambiguity protection).

7 A COMPOSITE RADAR MISSION: MULTIFREQUENCY , P BAND, X BAND INTERFEROMETRY.

We consider a planar structure terminated by two X band antenna (for interferometry purpose) with all the others other antenna panels employed for other radar mission, and possibly P band. The figure 7 gives a possible scenario X+P using the SAIL concept.

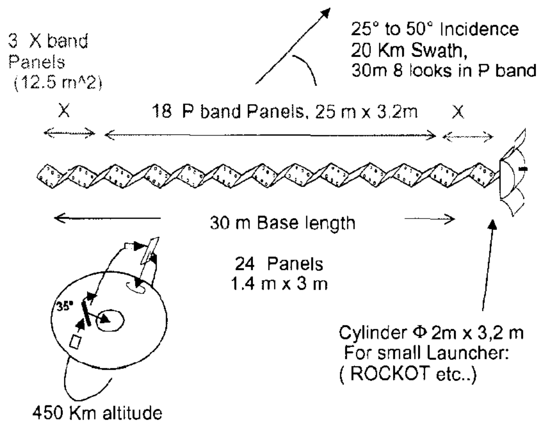

figure 7: Composite Radar Prism mission example

8 CONCLUSION

The RF Prism concept opens up new prospects for large antenna, particularly for two exciting SAR applications: P band and single pass interferometry. More work should be needed to get a full understanding of the opportunities offered by this concept in space based radar.

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